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Ultrasonic velocities in cast aluminium alloy–shell char particle composites

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Aluminium–ceramic particle composites are technologically important because of their good anti-abrasion and anti-friction properties. These composites have hitherto been produced by relatively expensive powder-metallurgy techniques and their uses have consequently been restricted to specialist applications covering a few manufacturing industries. In recent years, considerable attention has been paid to evolving methodologies within the framework of conventional casting procedures for the processing of these composites on a cost-effective basis so that their appeal extends to wider sections of industries. Some of the aluminium–ceramic particle composites successfully prepared by liquid metallurgy techniques include those containing dispersions of alumina [1] and zircon [2] for anti-abrasion applications and mica [3] and graphite [4] for anti-friction applications. Another recent development concerns the successful dispersion of porous carbon in the form of coconut-shell char particles in aluminium alloy matrix and the cast composites have shown good anti-friction properties under dry conditions of sliding [5]. An attractive feature to be noted in this development, is that shell char is a renewable resource available in large quantities at costs much lower than graphite.

In this letter we report the ultrasonic velocity measurements made on cast aluminium alloy–shell char particle composites containing up to 30 vol % shell char. These measurements have been examined in the light of recent theoretical formulations on wave propagation in random particle composites. The usefulness of the ultrasonic measurements for non-destructive testing and evaluation of the composites has also been examined.

Composites containing up to 30 vol % coconut shell char particles were prepared by conventional casting techniques. The processing, in principle, consists of adding suitably pre-treated shell char particles (average size 125 μm, density 0.8 g cm^{-3} and with an assay of 84.85 wt % carbon, 1.1 wt % ash, 0.3 wt % phosphorus, 0.02 wt % sulphur, 4.2 wt % moisture and the rest volatiles) into the vortex created by the mechanical stirring of aluminium alloy matrix (Al–11.8 wt % Si with 3 to 4 wt % Mg) melts and casting the melts containing the suspended shell char particles either under gravity or under pressure in suitable permanent cylindrical moulds. Fuller accounts of composite preparation, including particle pre-treatment procedures for promoting wetting between the particles and the matrix, are given elsewhere [5].

For ultrasonic measurements, specimens of 50 mm diameter by 25 mm length with plane parallel end faces were machined out of the cylindrical castings. A commercial pulse-echo type of apparatus [6] was used with PZT transducers. Longitudinal velocity measurements were performed at 2 MHz.

Measured values of longitudinal velocities for the composites are plotted as a function of particle concentration in Fig. 1. It can be seen from this figure that the effect of addition of shell char particles to the aluminium alloy matrix is to decrease the velocity. For instance, addition of 30 vol % shell char to the alloy matrix leads to a decrease of almost 16% in the longitudinal ultrasonic velocity. This is to be expected [7] because the elastic moduli of the dispersed particles [8] are considerably less than those of the matrix [9].

It will now be instructive to compare the experimentally measured velocities with the theoretically calculated values. In this regard, the formulation of Datta and co-workers [10, 11] seems to be very relevant to the particle composites of this study. Datta's formulations are essentially based on Lax's [12] quasi-crystalline approximation. The important assumptions here include that the particles are homogeneous, randomly distributed and in welded contact with an elastic matrix. Furthermore, an effective plane wave moves through the medium with a characteristic wave velocity, namely the effective wave velocity. Under this scheme, the longitudinal wave velocity in the composite for the case of spherical particles is given by

$$\left(\frac{\langle V_1\rangle}{V_1}\right)^2 = \frac{(1 + 3xT_{01}^{01})\left\{\left[1 + xT_{00}^{00}\left(1 + \frac{3}{2}\frac{\beta^2}{\alpha^2}\right)\right]\right\}}{\left\{1 - x\left[5T_{02}^{02}(1 + xT_{00}^{00}) - xT_{02}^{02}\left(1 + \frac{3}{2}\frac{\beta^2}{\alpha^2}\right) - x5T_{02}^{02}\right]\right\}} \quad (1)$$

where

$$T_{00}^{00} = \frac{1 + \sigma}{3(1 - \sigma)}\bar{A}$$

$$T_{01}^{01} = \frac{1}{3}\left(\frac{\varrho'}{\varrho} - 1\right)$$

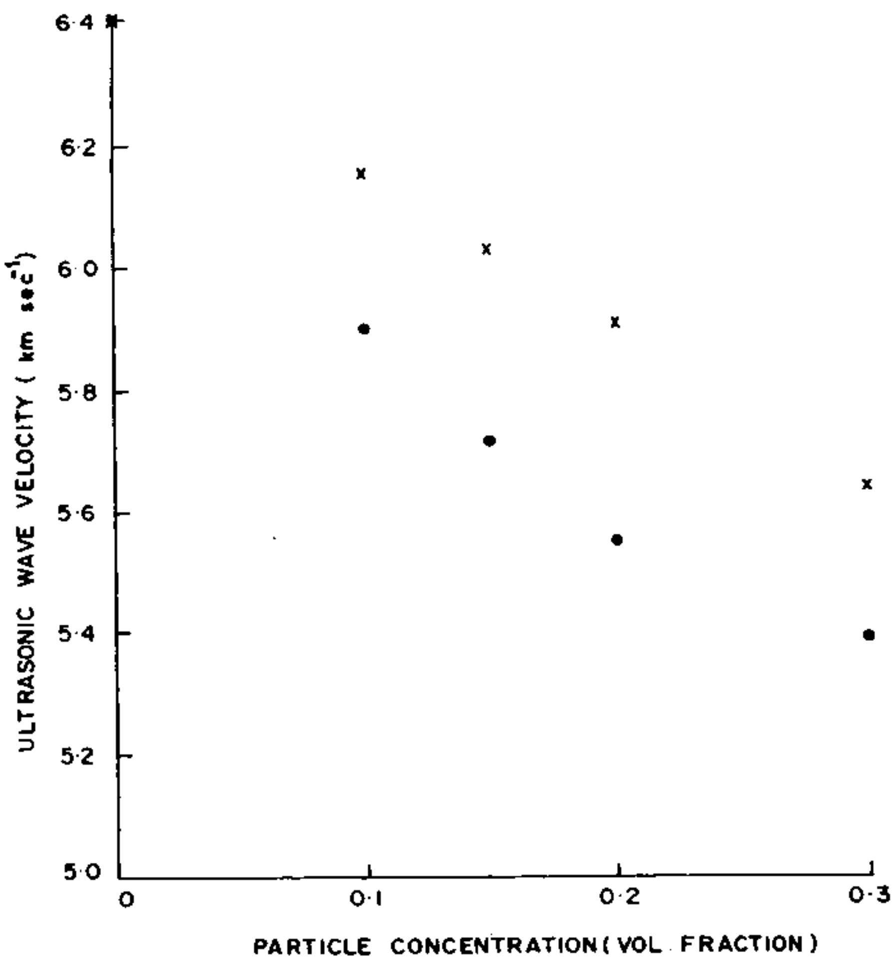

Figure 1 Variation of longitudinal ultrasonic wave velocity with shell char concentration. x, Theory; ●, experiment.

$$T_{02}^{02} = \frac{2(1 - 2\sigma)}{15(1 - \sigma)} \bar{B}$$

$$\bar{A} = \frac{[K'/(K - 1)]}{[\alpha(1 - K'/K) - 1]}$$

$$\alpha = \frac{1 + \sigma}{3(1 - \sigma)}$$

$$\beta = \frac{2(4 - 5\sigma)}{15(1 - \sigma)}$$

$$\bar{B} = \frac{[G'/(G - 1)]}{[\beta(1 - G'/G) - 1]}$$

and $\langle V_1 \rangle$ is the effective longitudinal velocity in the composite; V_1 is the longitudinal velocity in the alloy matrix; x is the volume fraction of the particles; ϱ is the density of the matrix; ϱ' is the density of the particles; σ is Poisson's ratio of matrix; K, K' are the bulk moduli of matrix and particles, respectively; and G, G' are the shear moduli of matrix and particles, respectively.

After taking the appropriate values for the density and elastic constants of the particles and the matrix [8, 9], the values of $\langle V_1 \rangle$ for the various particle concentrations studied here have been calculated using these formulations. These theoretical velocities are included in Fig. 1 and also tabulated in Table I along with the experimentally measured values. Included in this table is the discrepancy between the theoretical and experimental values expressed as a percentage.

It can be seen from Fig. 1 and Table I that the experimentally measured velocities are all less than the corresponding theoretically calculated values. Because the theoretical formulations for the velocities are for a model two-phase system of homogeneous spherical particles randomly distributed in a truly elastic matrix with perfect particle–matrix bonding and no porosity, the discrepancy observed between the experimental and theoretical velocities should be a measure of the deviations in the microstructure of the cast composite from that of the ideal microstructure of the model system. In other words, the ultrasonic velocity measurements used in conjunction with the theoretical formulations can afford a basis for quick nondestructive evaluation of the composites.

Although the discrepancies observed between the experimental and theoretical velocities for the composites studied here are not large (Table I), it will be instructive to examine the factors contributing to this at the microstructural level. Of particular interest here is the bond between the shell char particles and the

TABLE I Experimental and theoretical values of longitudinal ultrasonic wave velocities

Vol. fraction of particles (x)	Longitudinal velocity in the composite, $\langle V_1 \rangle$ (km sec^{-1})		Discrepancy between theoretical and experimental velocities (%)
	Experimental	Theory	
0	6.4	6.4	0
0.1	5.9	6.156	4.16
0.15	5.721	6.031	5.14
0.2	5.552	5.904	5.96
0.3	5.394	5.642	4.39

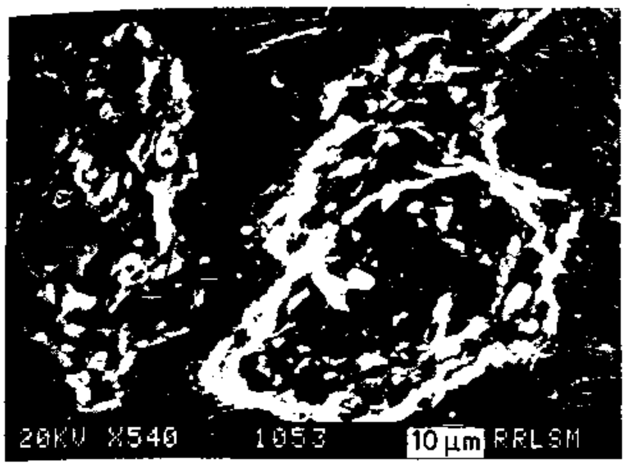

Figure 2 Scanning electron micrograph of composite containing 30 vol % shell char showing well-bonded particles.

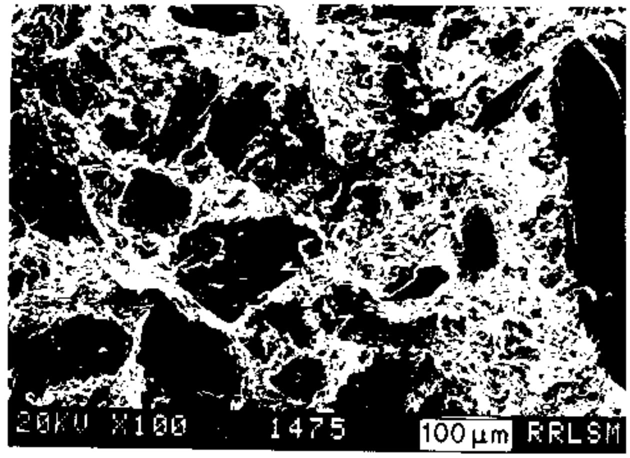

Figure 3 Fractograph of composite containing 30 vol % shell char showing cleavage fracture of particles.

alloy matrix because a good interfacial bond is a prerequisite for obtaining a useful composite. To gain further insight into this bonding, we have taken scanning electron micrographs and also carried out electron-probe microanalysis of the particle–matrix interface. The bright lacing around the particles seen in the scanning electron micrograph (Fig. 2) has been found to be a reaction layer comprising magnesium and silicon. This reaction zone firmly bridges the poorly wettable shell char particles with the aluminium alloy matrix. That this interface contributes to the stress transfer from matrix to particle during tensile loading can be inferred from the fractograph (Fig. 3), which depicts the cleavage fracture of the particles.

In the light of these findings it appears that the particle–matrix interface is unlikely to be the major factor contributing to the observed discrepancies between the experimental and theoretical velocities. It is plausible that many of these discrepancies result from a combination of the effects of other microstructural features such as porosity, agglomeration and non-sphericity of the particles.

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